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http://cism.jpl.nasa.gov/ehw

Evolvable Hardware for Extreme Environments:

Expanding Device Operational Envelope through Adaptive Reconfiguration

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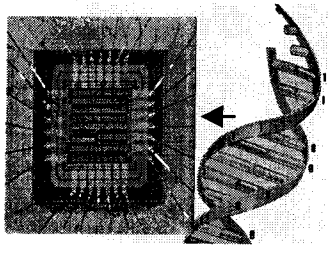

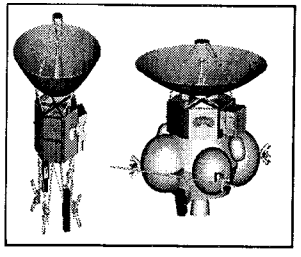

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The Message

- *Evolvable hardware*

(i.e. hardware that self-configures under control of adaptation/ evolutionary algorithms)

can preserve/ recover system functionality by reconfiguration/ morphing.

- If device characteristics change with temperature, one can preserve the function by finding a different circuit solution, which exploits the altered/modified characteristics.

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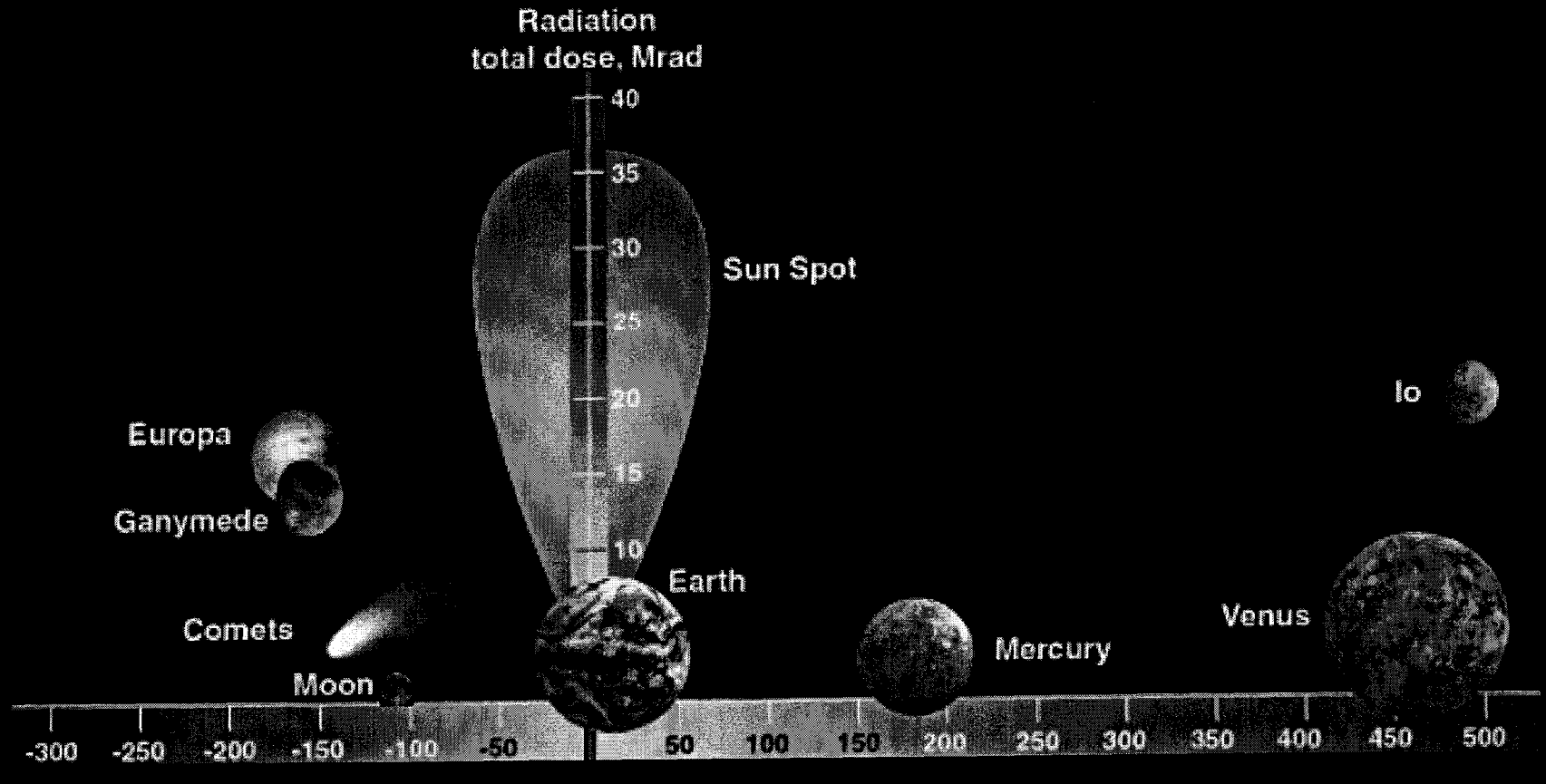
Contents

- "New lifestyles for future S/C" or

"May you live long and survive harsh environments"

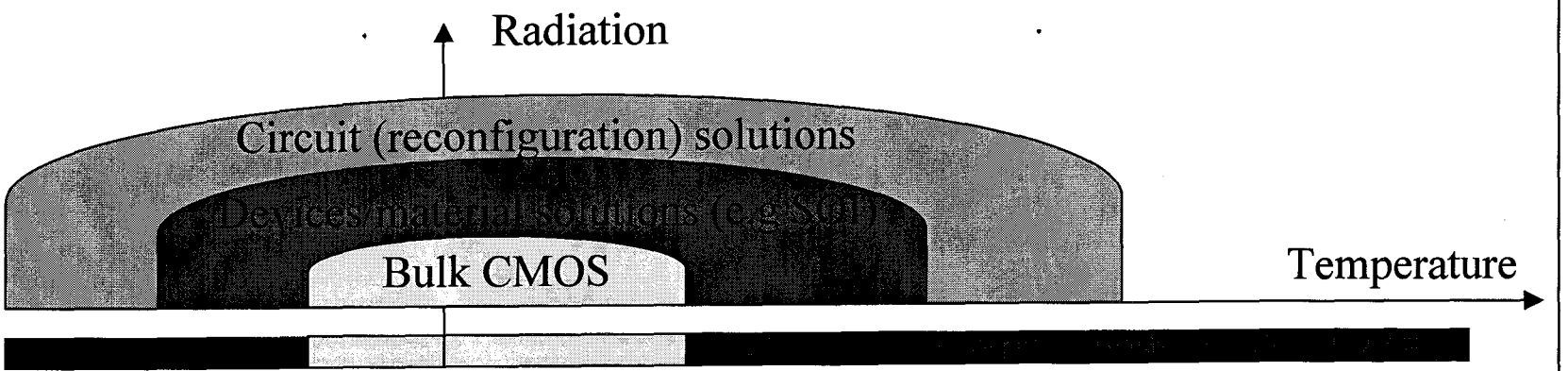
- EHW - determining new configurations automatically
- T changes? Change configurations to preserve function
- Experimental results @-200C, @+250C
- Conclusion and vision

Planetary Extreme Environments

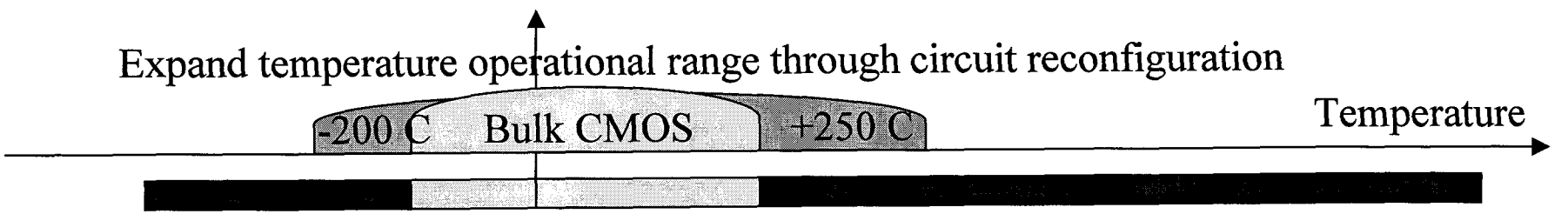


Expanding Operational Envelope through Adaptive Reconfiguration (A Circuit Solution)

- **Claim: Circuits solutions can further expand the operational envelope, and should be considered in addition to device solutions**

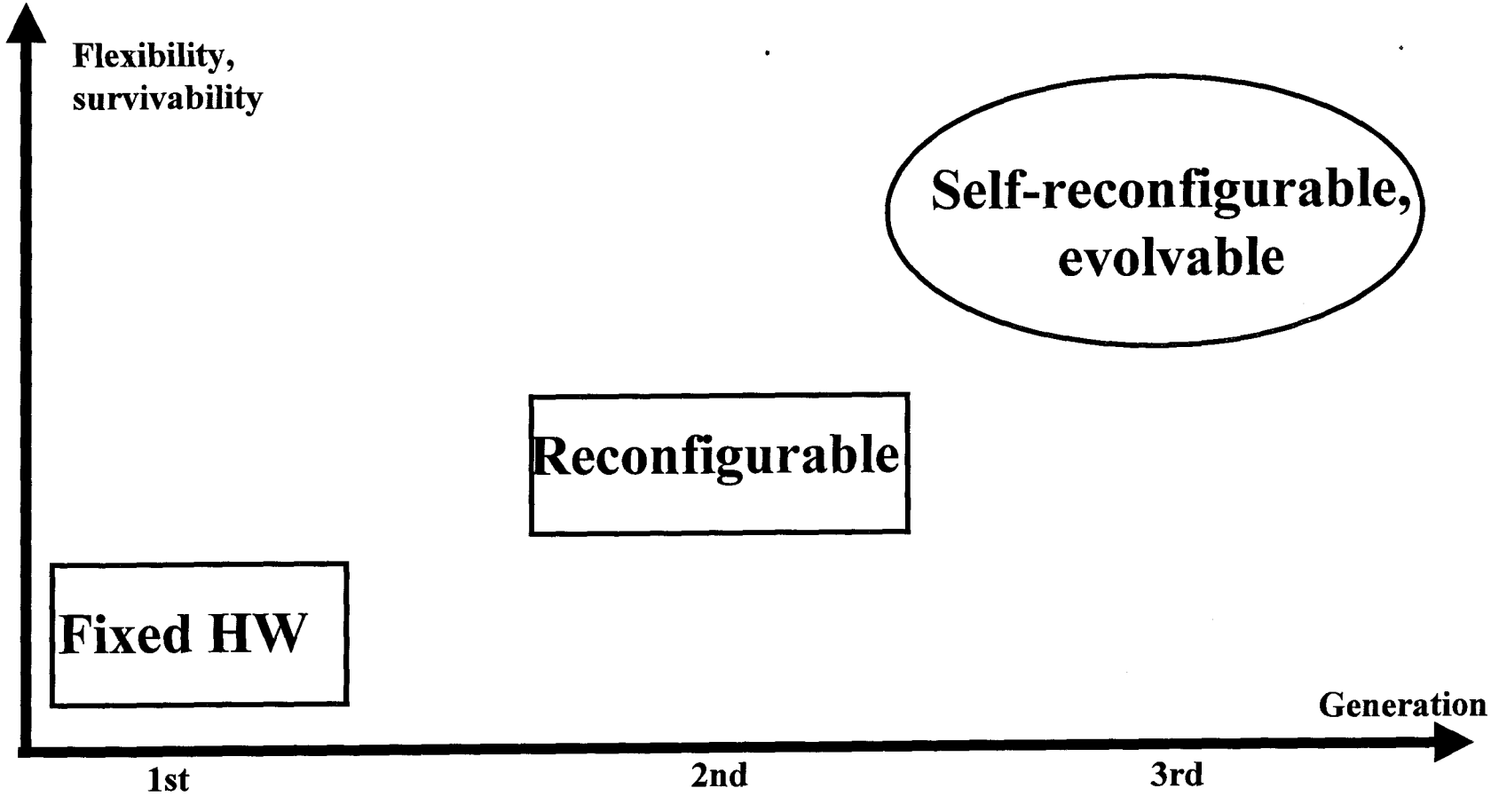


- **Demo: Circuits solutions can expand the operational envelope of current devices**



- **Limitations are of the ensemble device/configuration, not of the device(material) only**

Generation changes in avionics: from fixed HW to evolvable HW



EHW for Survivability and Versatility

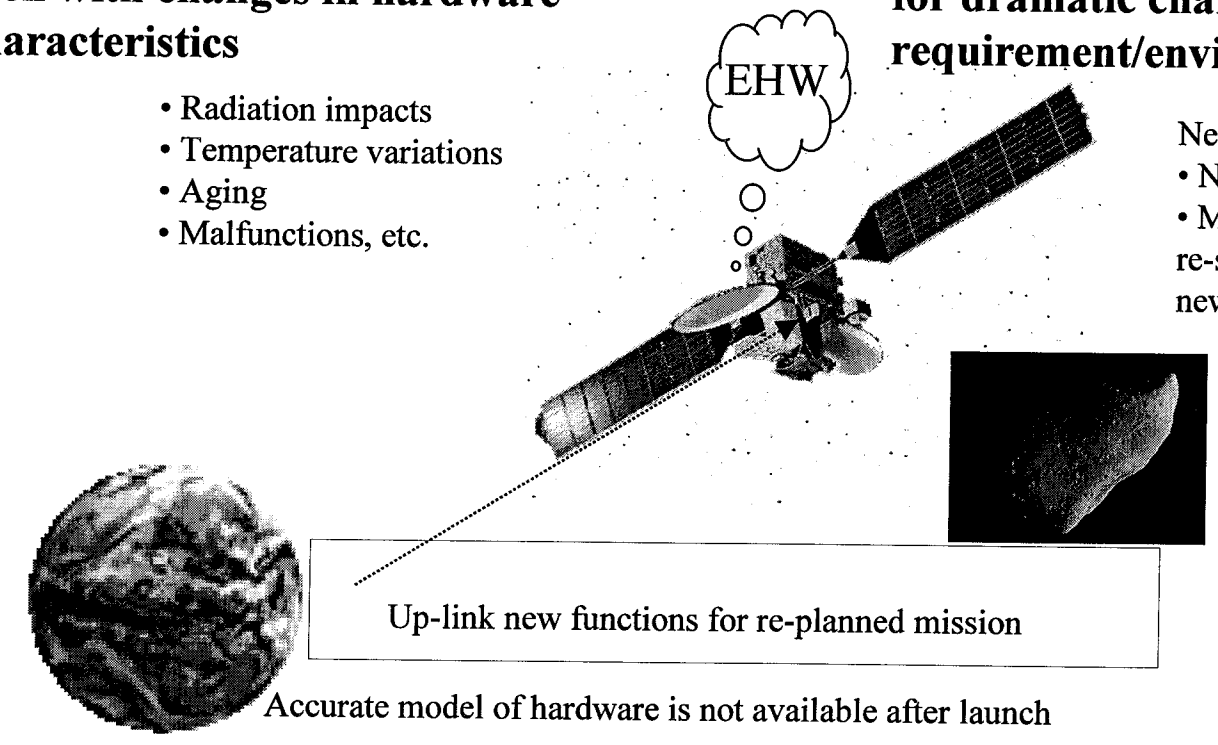
Enable long-life (100+ years) survivable spacecraft

Survivability: Maintain functionality through parametric adjustments even with changes in hardware characteristics

- Radiation impacts
- Temperature variations
- Aging
- Malfunctions, etc.

Versatility: Create new functionality through synthesis of totally new circuits for dramatic changes in requirement/environment

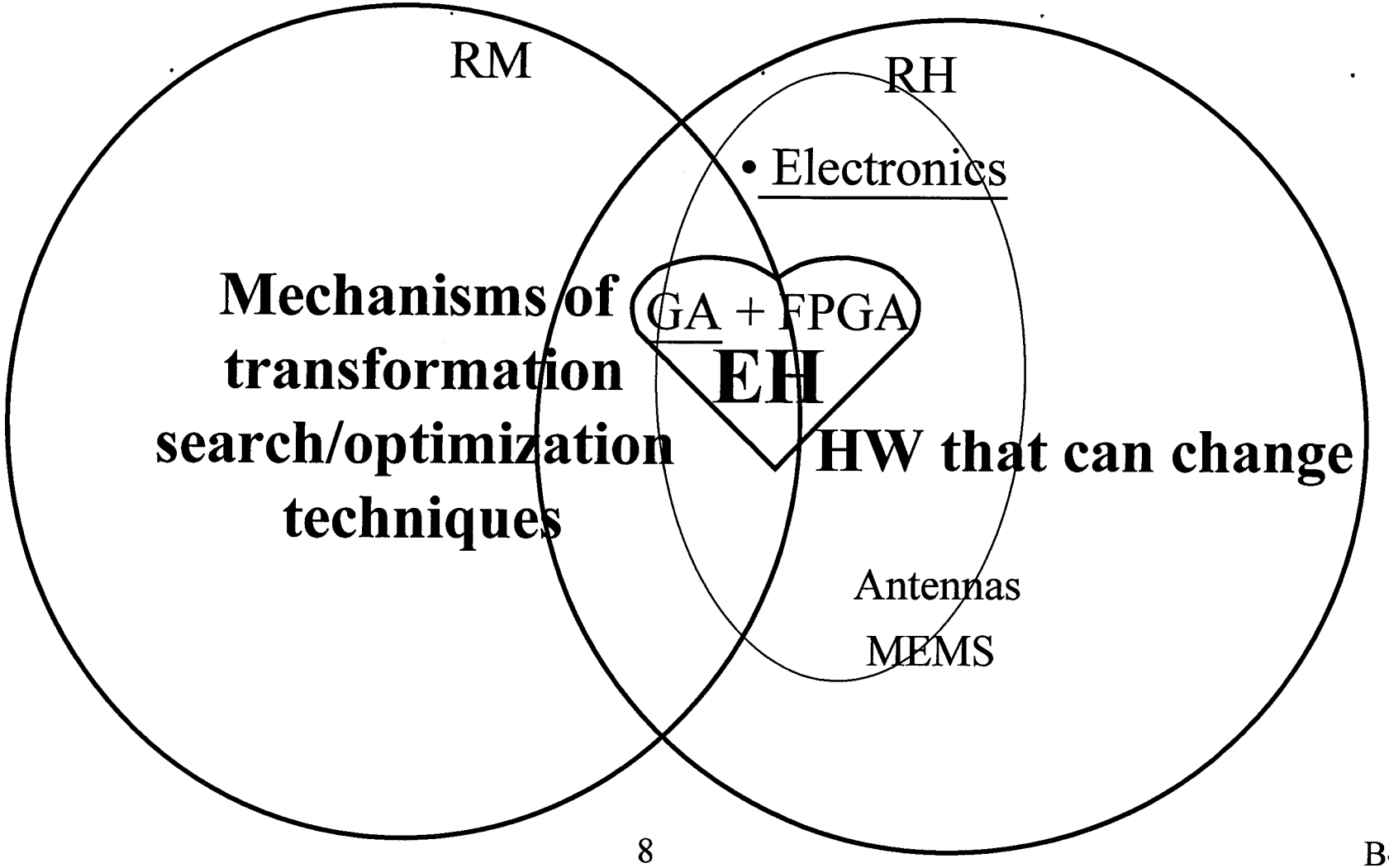
New functions required for:
- New mission phases
- Missions where findings require re-scooping to take advantage of new opportunities



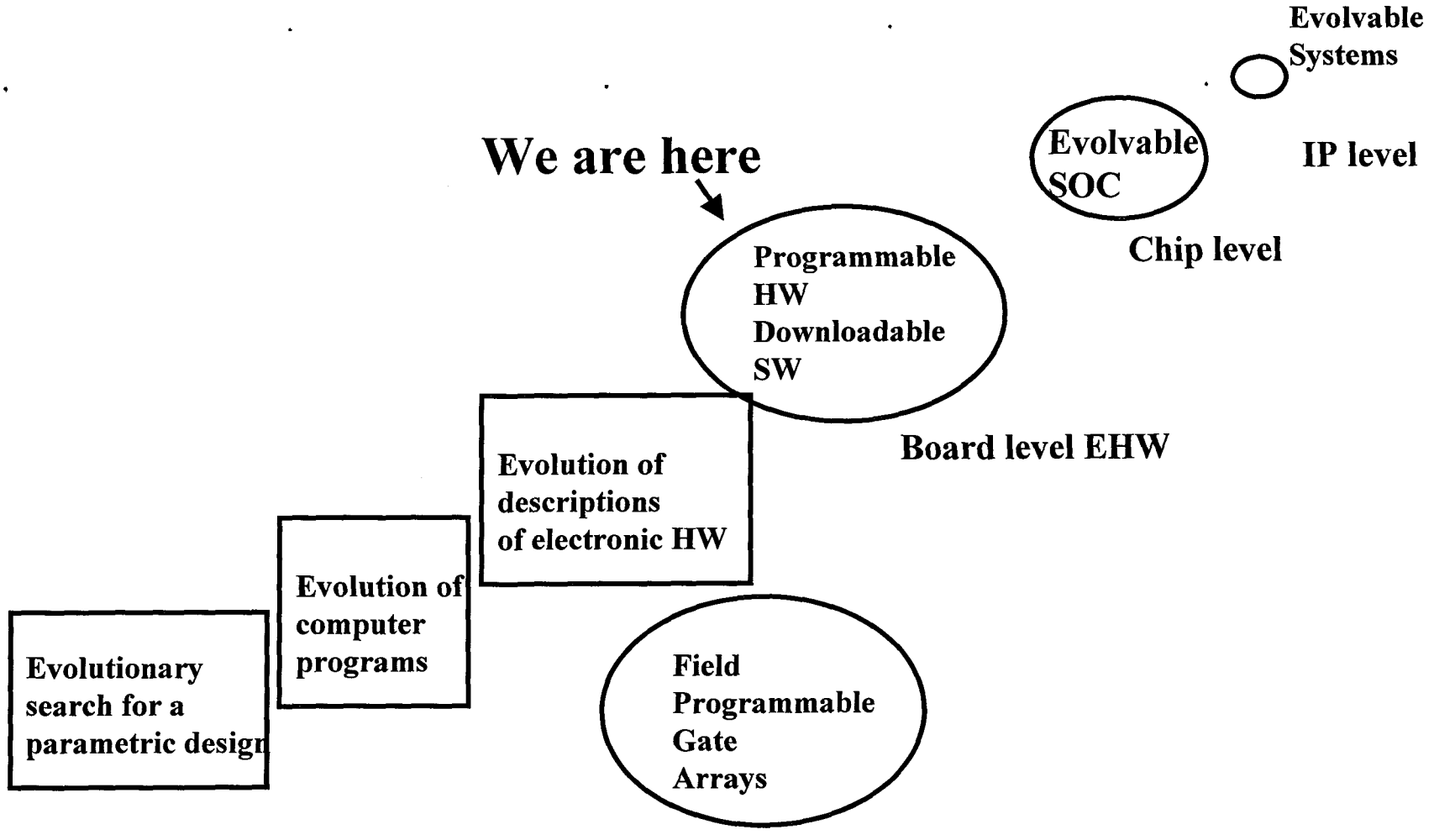
Accurate model of hardware is not available after launch

Evolvable Hardware =
Reconfigurable Mechanism + Reconfigurable Hardware

EHW=RH+RM



Evolution of evolvable HW



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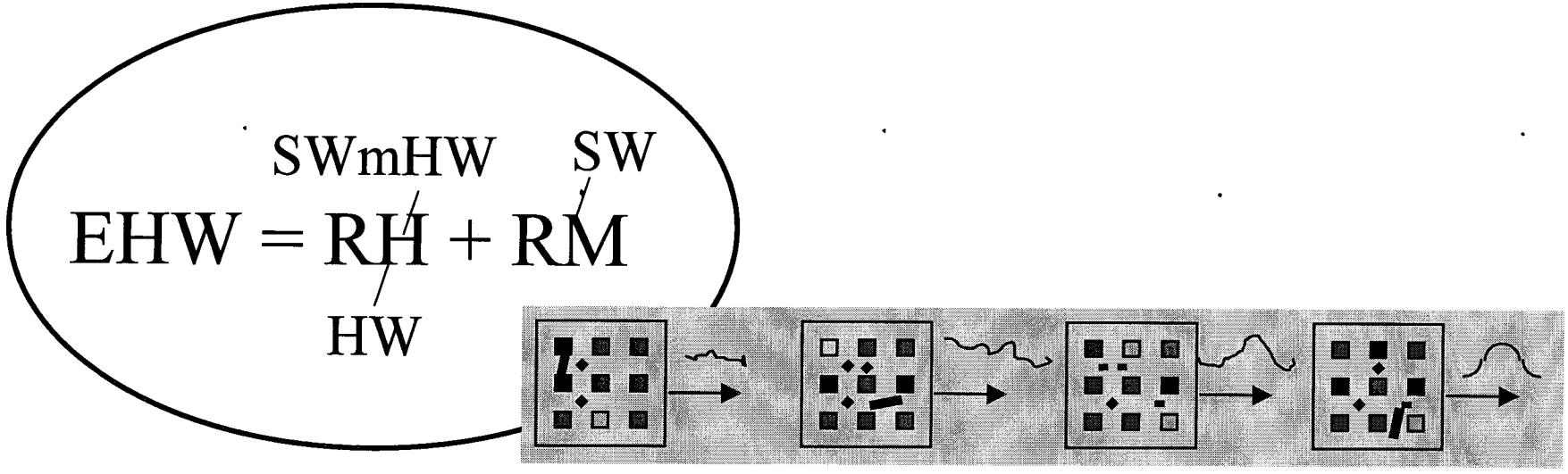
Evolvable Hardware:
reconfigurable hardware + reconfiguration mechanism



Approach to EH implementation:

- Use RH- reassign cell function/interconnection
- Use powerful parallel searches (e.g., GAs) to evolve the hardware

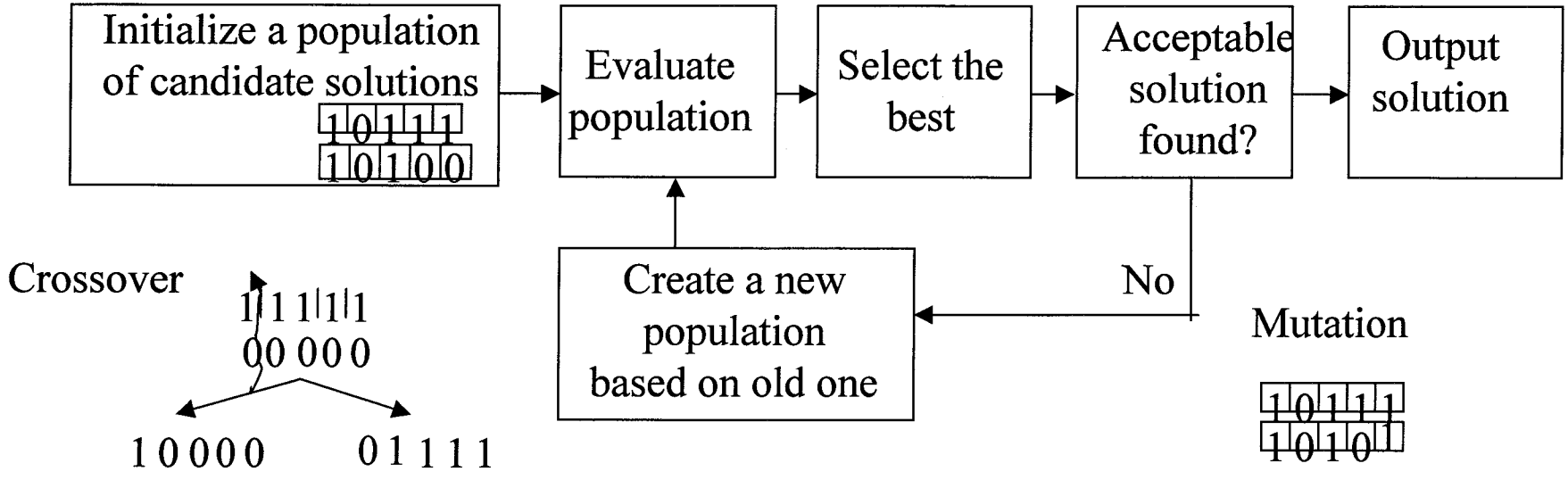
Plus

- Fast evaluation
- Low cost for failure

Reconfiguration mechanisms

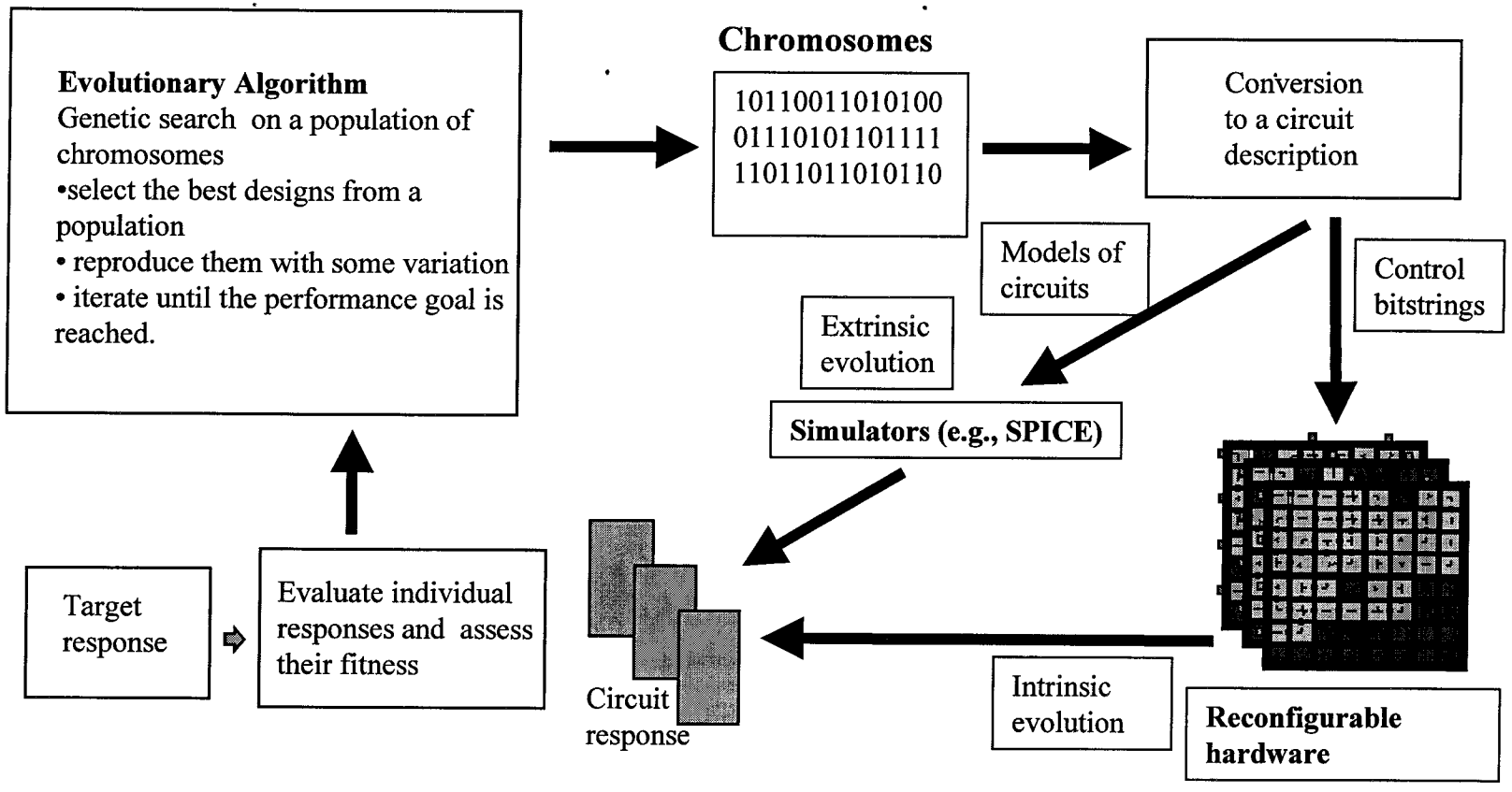
- RM: GA, ES, Hill Climbing, Taguchi Methods, etc.
- Most popular searches: population based, use "generate and test" strategies.

Sketch of a simple GA



Crossover and mutation are two common genetic operators used in creating a new population.

Evolvable Hardware in Electronics
Evolutionary synthesis and adaptation of electronic circuits



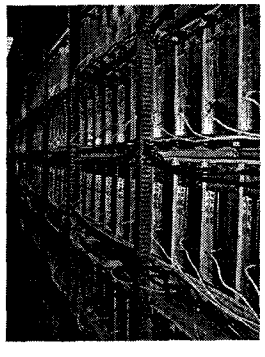
Potential electronic designs/implementations compete; the best ones are slightly modified to search for even more suitable solutions

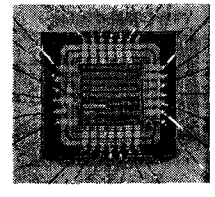
Why EHW in HW?

- Circuit design can be demonstrated in SW, but…
- takes huge resources (the photo on the bottom left shows Koza's computers, which run for days evaluating hundreds of thousands of circuits for thousands of generations!!)
- SPICE scales badly (time increases nonlinearly with as a function of nodes in netlist - in ~ subquadratic to quadratic way)
- *No existing hardware resources allow porting the technique to evolution directly in HW (and not sure will work in HW)*

- Examples by Koza* are predicted to take ~3 min in 2010 on desktop PC

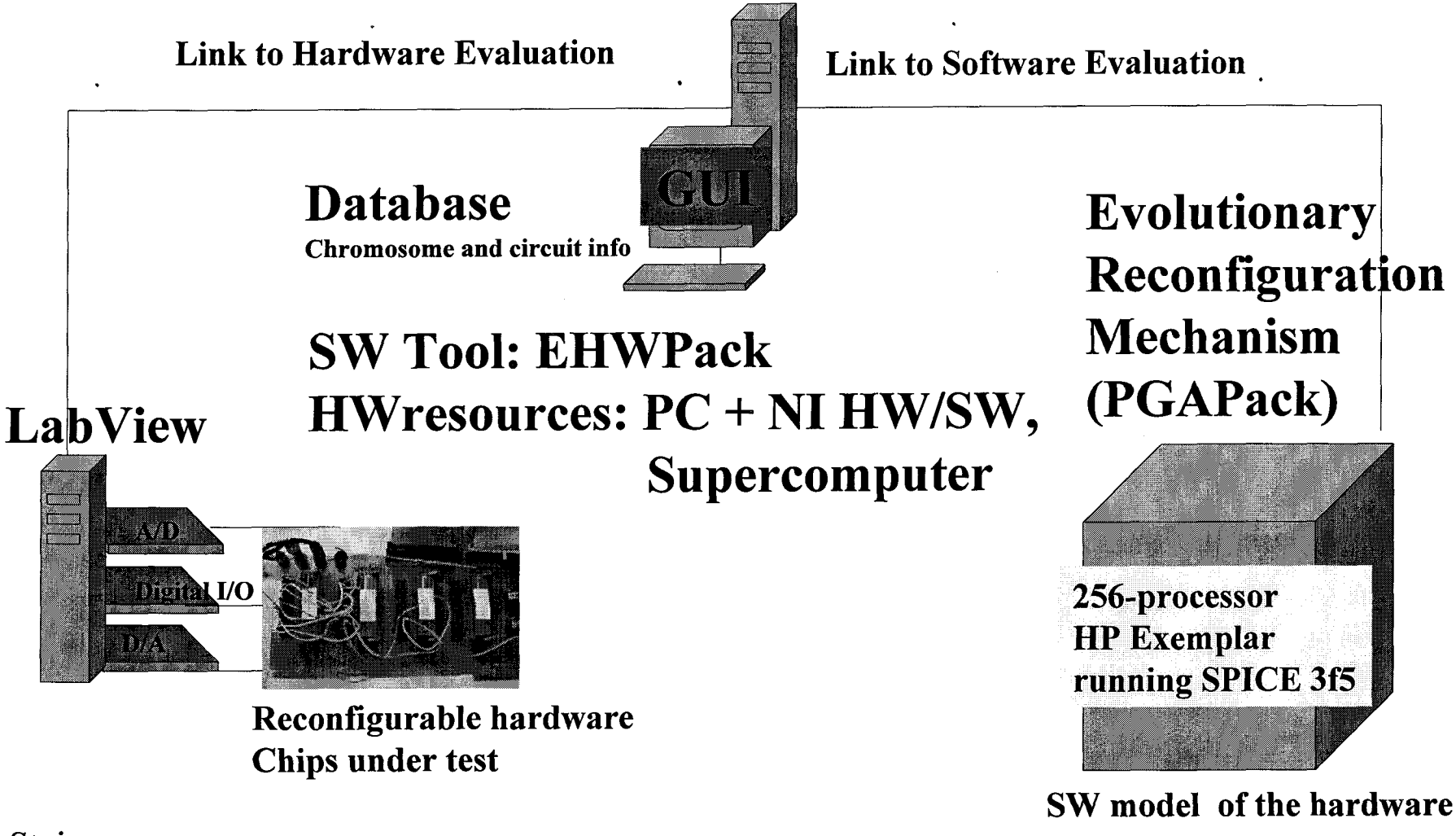
- JPL's VLSI chips will allow evolution 4+ orders of magnitude faster than SPICE simulations on Pentium II 300 Pro. (~ 3 min in 2001 for circuits of complexity >= Koza's).



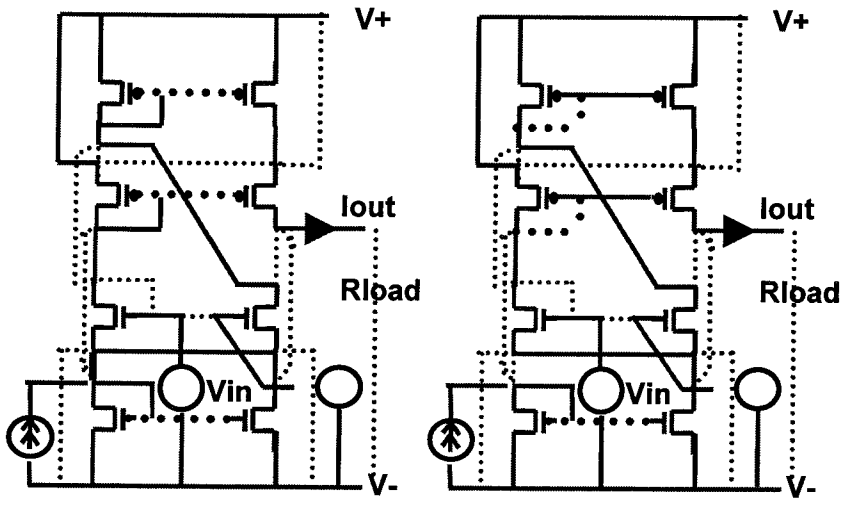


*J. Koza et al. "Genetic Programming III: Human competitive machine intelligence", MK, 1999
9 circuits in the book rediscover patented solutions in analog circuit design.

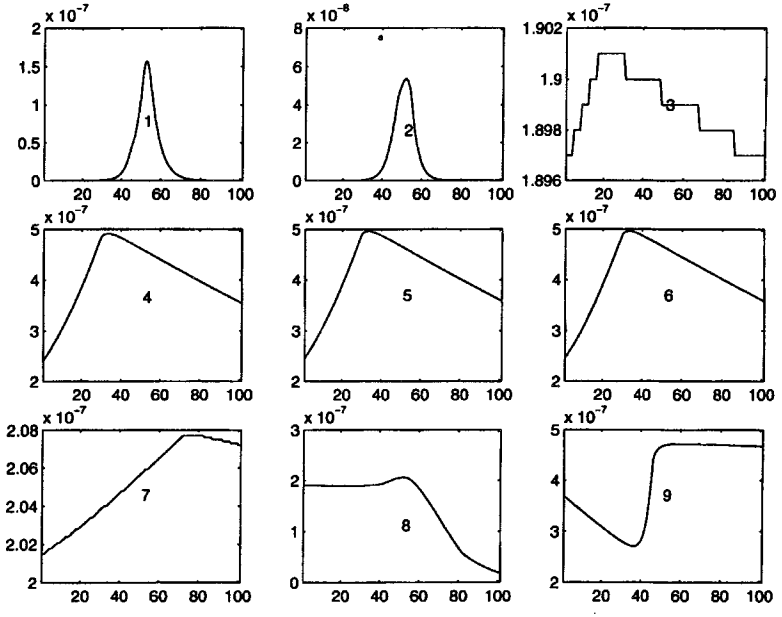
Testbed


Link to Hardware Evaluation
Link to Software Evaluation
GUI
Database
Chromosome and circuit info
SW Tool: EHWPack
HWresources: PC + NI HW/SW, Supercomputer
Evolutionary Reconfiguration Mechanism (PGAPack)
LabView
A/D
Digital I/O
D/A
256-processor HP Exemplar running SPICE 3f5
Reconfigurable hardware
Chips under test
SW model of the hardware

Circuits synthesized by evolution



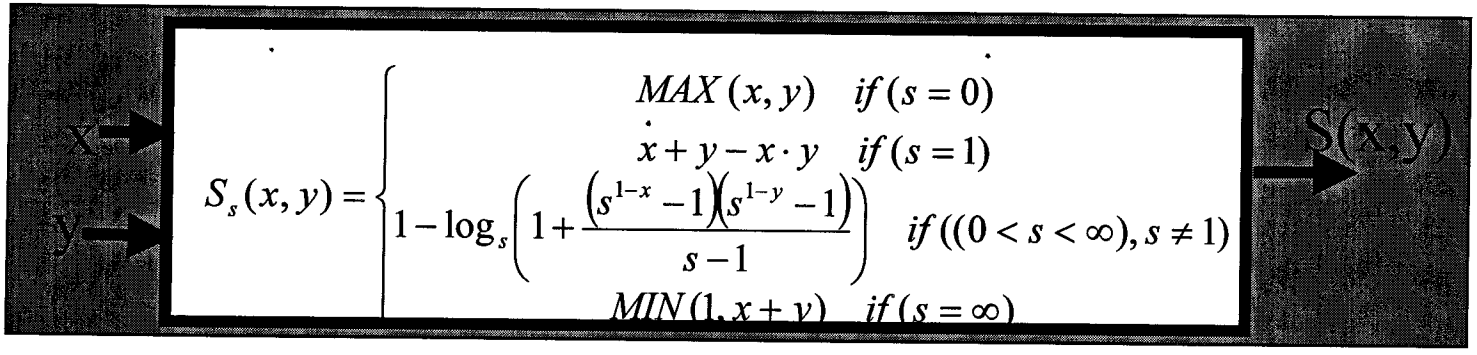
Unusual designs

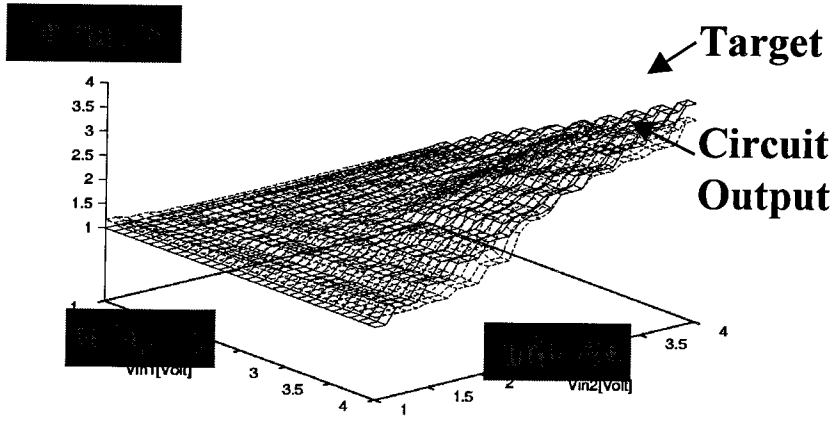


Best responses of a "generation"

Evolution of Computational circuits

Evolution of Fuzzy-Neuron Circuit



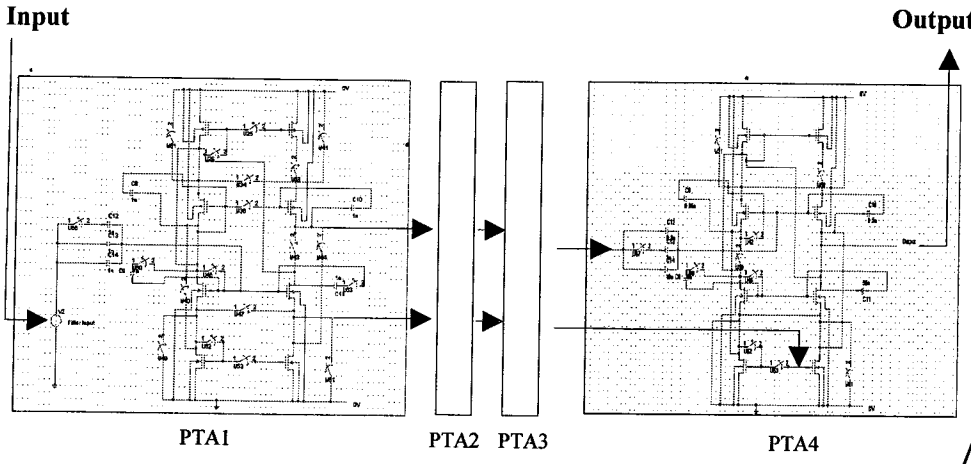


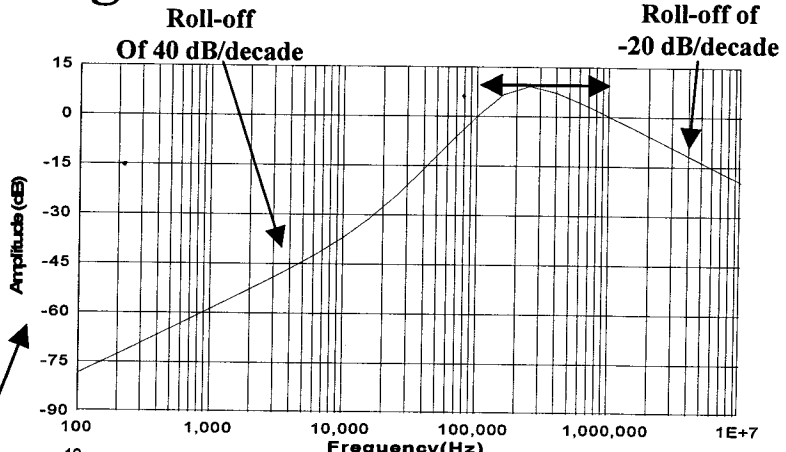
- Uses two FPTA cells (16 transistors)
- compact implementation

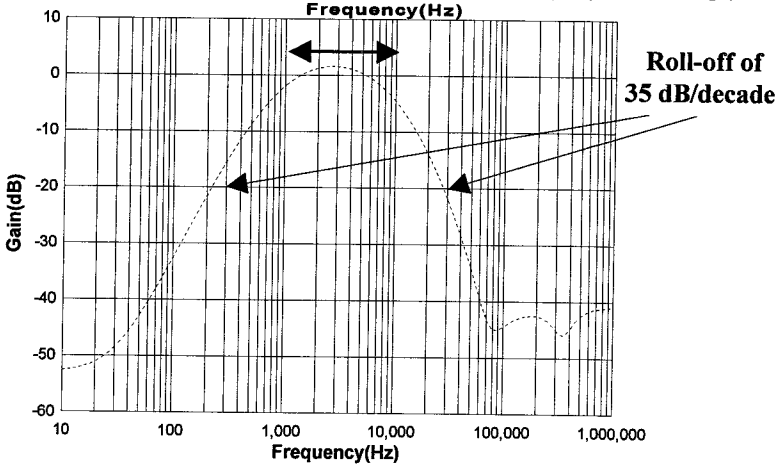
Stoica, A., In *Proceedings of the 30th IEEE Symposium on multi-valued logic*, Portland. May 2000.

Evolution of Filters

Evolution of band-pass filters using the FPTA modules







Example:

- Wide Band Filter: Gain of 10 dB between 100kHz and 1MHz with roll-off of 40 dB/decade before 100kHz and -20 dB/decade after 1Mhz.
- Narrow Band Filter: Gain of 2 dB between 1kHz and 10kHz with roll-off of -35dB/decade. Stop band below 100Hz and above 100kHz.

FPTA enable automatic synthesis of arbitrary filters using the same hardware resources

Zebulum et al., In *Third International Conference on Evolvable systems (ICES2000)*. Edinburgh, UK. April 2000.

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Function: effect of choice of devices and circuits

- Notation

  T : Temperature of operation. Could be an interval

  D(T) ={d1(T), d2(T), …, dn(t)} : Set of devices with various temp characteristics

  C : Circuit (topology, configuration). Describes interconnection of devices.

  F : Function of circuit

  f <----> {T, D(T), C}

  Simply stated: The function of a circuit depends on the characteristic of devices, temperature and circuit configuration.

Change in the design approach: not one circuit configuration but several

f_1, T1, D(T1) ---> C

For desired function, given operational temperature T1, and D, a set of devices of with certain temperature dependent characteristics, find a circuit topology/configuration C.

I propose here f, T, D(T) ---> C(T)

current approach

fA, T1, D(T1) ---> C

T2, D(T2), C ---> fB

C is fixed, we are stuck

proposed approach

design for T1

fA, T1, D(T1) ---> C(T1)=c1

when temp becomes T2

T2, D(T2), C(T1) ---> fB

C can change, search again

find c2=C(T2) which gives T2, D(T2), C(T2) ---> fA

fA, T2, D(T2) ---> C(T2)=c2

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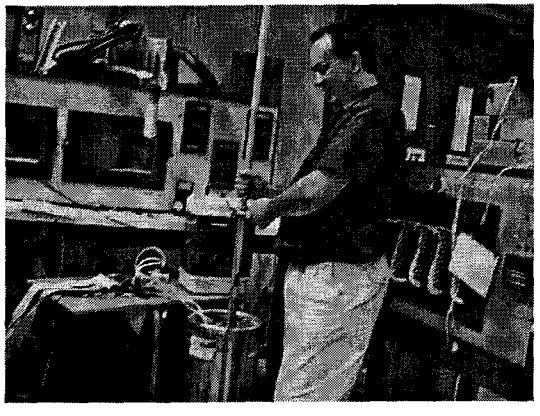
Steps of the temperature experiment:

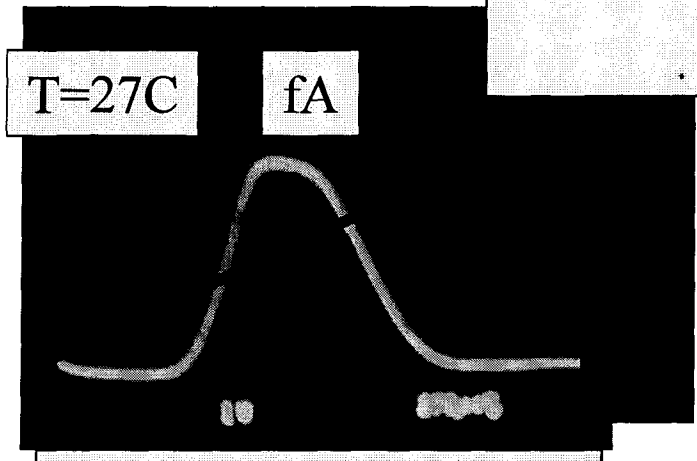
1. Get human design or evolutionary design of a circuit at 27 C
2. Expose chip to low/high temperature and observe degraded response
3. Apply evolution, and obtain a new circuit solution, which recovers functionality



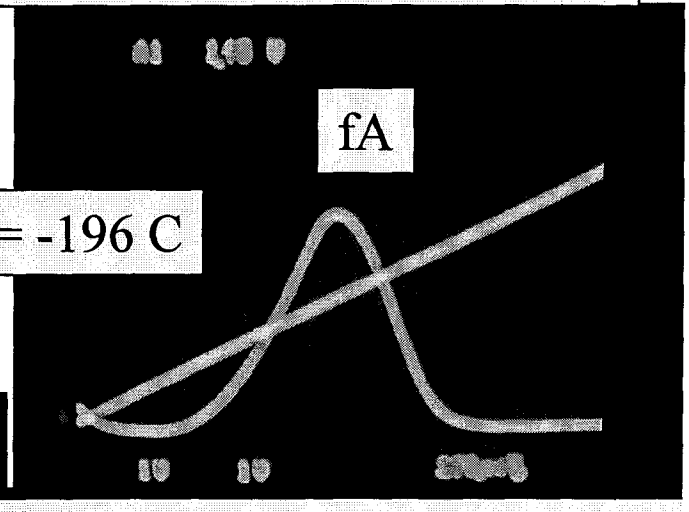
Immersing the chip under test in liquid nitrogen

Functional Recovery at Low Temperatures

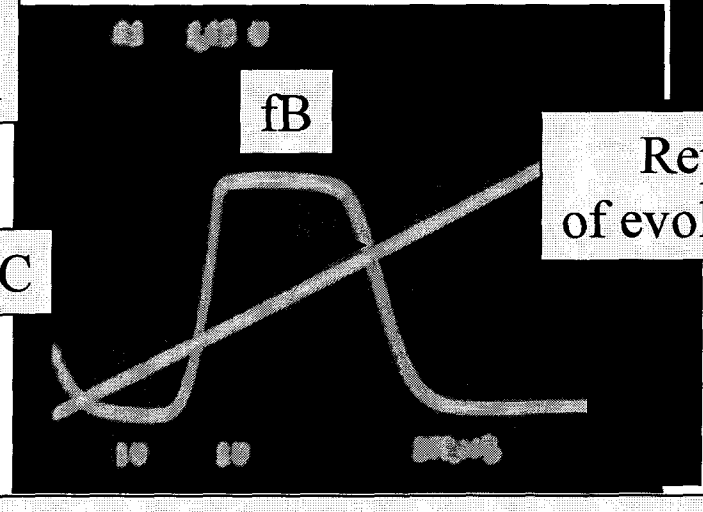
fA ={T1, D(T1), C(T1)}={T2, D(T2), C(T2)}
{T2, D(T2), C(T1)}= fB



Functional response
of original circuit design



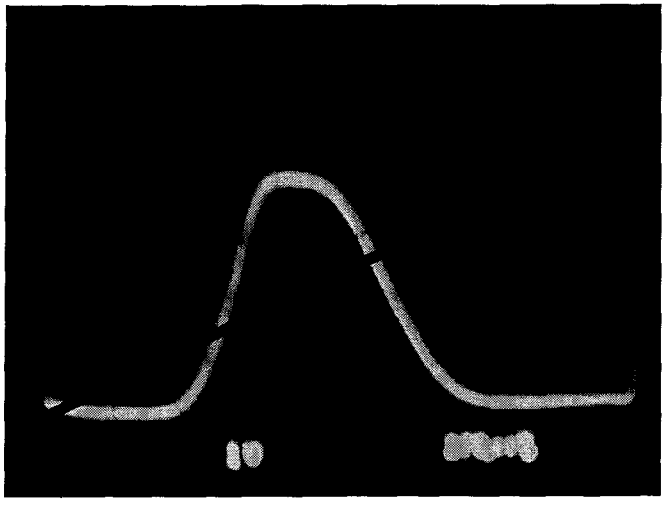
Repaired functional response
of evolved new circuit configuration



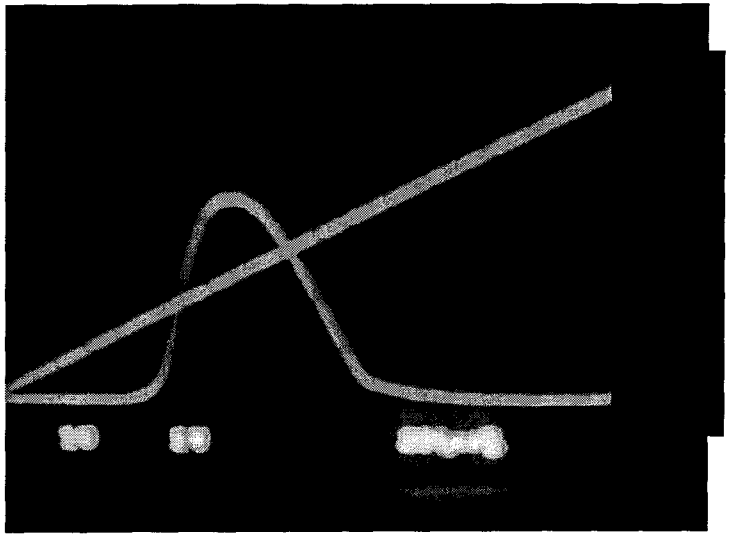
Functional response of original circuit
affected by temperature

Functional Recovery at High Temperatures

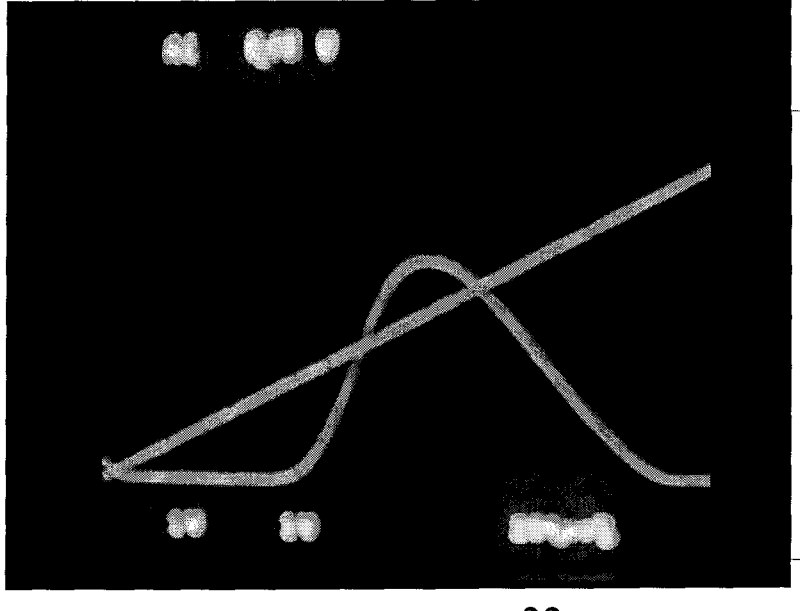
T= 27C



T= 245C



T= 245C



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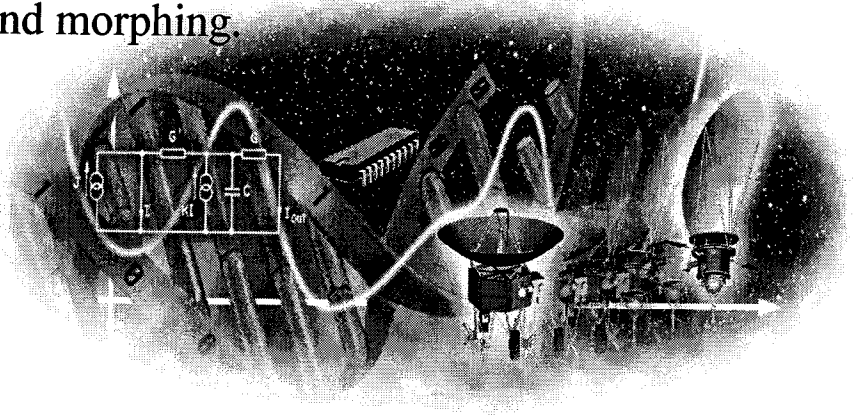
Discussion/Conclusion

- Initial experiments, although very simple, demonstrate the new concept of extending functionality at extreme temperatures through hardware (self) reconfiguration
- Fine granularity probably helps - bigger search space, more flexibility
- How difficult is for more complex circuits?

Vision for EHW for Space - 2020

- EHW has the potential to be the underlying technology behind the avionics infrastructure of the space systems for 2020 and beyond. Future avionics may evolve not only electronics but also smart optical/structural subsystems through reconfiguration and morphing.



- EHW technology will enable:
  - Reconfiguration for multiple functionality of avionics systems using the existing resources.
  - Adaptation for new needed functionality
  - Fault-tolerance and self-healing for recovering functionality by rerouting around damaged components and reusing components with modified/altered characteristics in new circuit topologies.
  - Autonomous avionics through self-configuration.